Metal-loaded Liquid Scintillator

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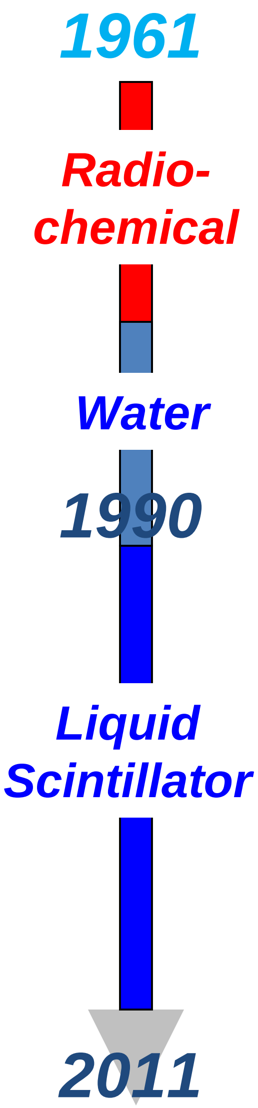
The Trend of Neutrino Detector



- ***HOMESTAKE** Radiochemical Detector*
  615 tons of C_2Cl_4; $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$ (~40 years)
- ***GALLEX** Radiochemical Detector*
  30 tons of Ga; $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$ (1986 - 1998)
- ***SNO** Water Čerenkov Detector (SNOLab)*
  1-k tons of ultra-pure D_2O (1996 - 2006)
- ***Long-Baseline Neutrino Experiment (LBNE)***
  V_μ beam from accelerator to DUSEL (began~2002)
- ***High-Precision Reactor θ_{13}** Real-time Detector (Project)*
  200 tons of 0.1% Gd in Liquid Scintillator (began ~2003)
- ***SNO+ Neutrinoless Double Beta Decay** Real-time Detector (R&D)*
  1-k tons of 0.1% Nd in Liquid Scintillator (began ~2005)
- ***LENS** Real-time LS Detector (R&D)*
  100 tons of ~8% ^{115}In in Liquid Scintillator (began ~2000)
- ***Neutrino Application***
  - ***Geo-neutrino and/or Nonproliferation and/or Reactor Monitoring***
  - ***Li/Ca-loaded Liquid Scintillator (began 2008)***

What do we need from M-LS?

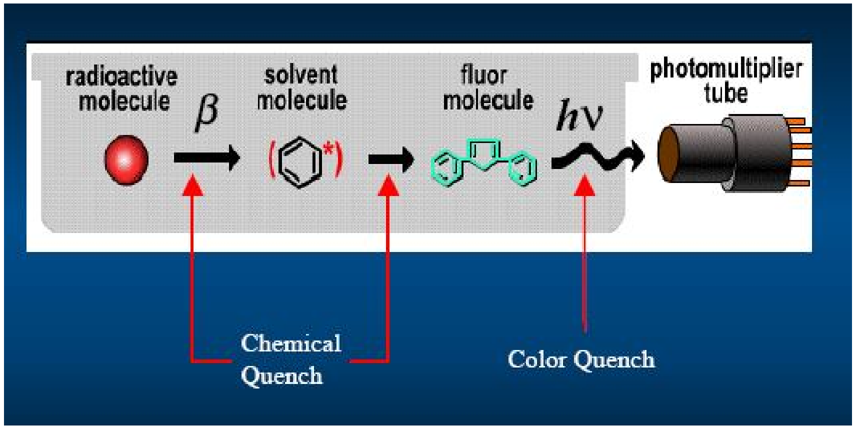
- *Preparation of high-quality M-LS must be Reliable and Reproducible:* ***long-term stability*** *and* ***long attenuation length with suitable photon-production***
- ***At BNL:***
  - *Solvent-extract organometallic compound into LS with carboxylic acid, RCOOH*
  - *Study effects of inclusion in organic phase of OH-, H_2O, free carboxylic acid, Cl-*
  - *Characterize how parameters affect light yield, chemical stability, final metal ions dissolved in LS, and chemical composition*
  - *Develop a variety of chemical techniques for chemical/radioactive purifications of all starting materials, which is the key of clean M-LS*
  - *Remove the U/Th/K from the starting materials to increase the sensitivity*

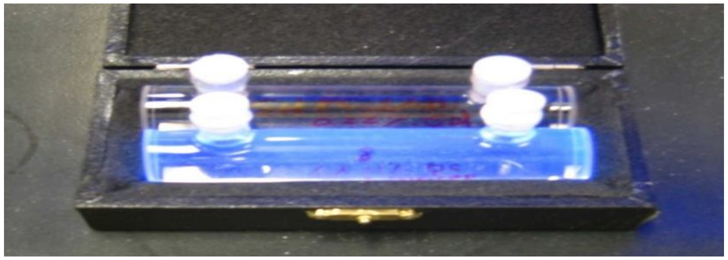
M-LS Criteria for Neutrino Experiments

- *Long-term Stability: > 3 years*
- *Long attenuation length: > 10 m*
- *High photon yield*
- *Low radioactive background*
- *ESSH*

Components of LS

- ***Aromatic solvent*** *that contains a high density of π-electrons for energy transfer*
- ***Fluor*** *that transfers the energy (<400 nm) to light (>400 nm) within the optimal detection range of PMT*





Metal selection for different experiments

- *Nd for SNO+*
  - *Serve as a double-beta decay target*
  - *Large Q(3.37 MeV) and favorable matrix element*
- *Gd for Daya Bay*
  - *Enhance neutron-capture cross section*
  - *Shorten neutron capture time*
  - *A high release energy from capture, good for suppressing background*
- *In for LENS*
  - *Low threshold*
  - *Directly measures neutrino energy*
  - *Triple tag effect*

Selection of Liquid Scintillator

- *High density, flash point, low toxicity, and low cost*
- *Chemical compatibility*
- *High light yield and long attenuation*
- *Able to load organometallic compound*

Study of Liquid Scintillator

	Gd Loading	d (g/cm^3)	UV Abs^{430} before / after	Abs_{260}	n^{20}	Light Yield	H atoms‡ per c.c	Flash Point
PC	Yes	0.889	0.008 / 0.002	2	1.504	1	5.35×10^{22}	48 C
PCH	Yes	0.95	0.072 / 0.001	1.7	1.526	0.46	5.71×10^{22}	99 C
DIN	Yes	0.96	0.040 / 0.023	>10	-	0.87	5.45×10^{22}	>140 C
PXE	Yes	0.985	0.044 / 0.022	2.1	-	0.87	5.08×10^{22}	167 C
LAB	Yes	0.86	0.001 / 0.000	1	1.482	0.98	6.31×10^{22}	130 C
Mineral Oil C_{24}~C_{28}	No	0.85	0.002 / 0.001	1	~1.46	~	$6.73 – 8.00 \times 10^{22}$	215 C
Dodecane	No (<20%)	0.75	0.001 / 0.000	1	1.422	~	6.89×10^{22}	71 C

M. Yeh et. al Nuclear Instruments and Methods in Physics Research Section A: Gadolinium-loaded liquid scintillator for high-precision measurements of antineutrino oscillations and the mixing angle, θ13 Volume 578, Issue 1, 21 July 2007, Pages 329-339

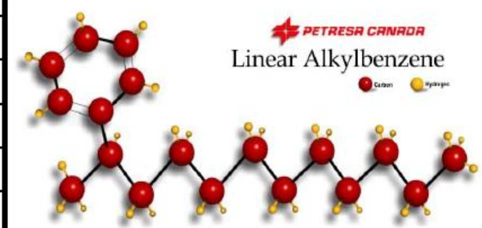
LAB Specification

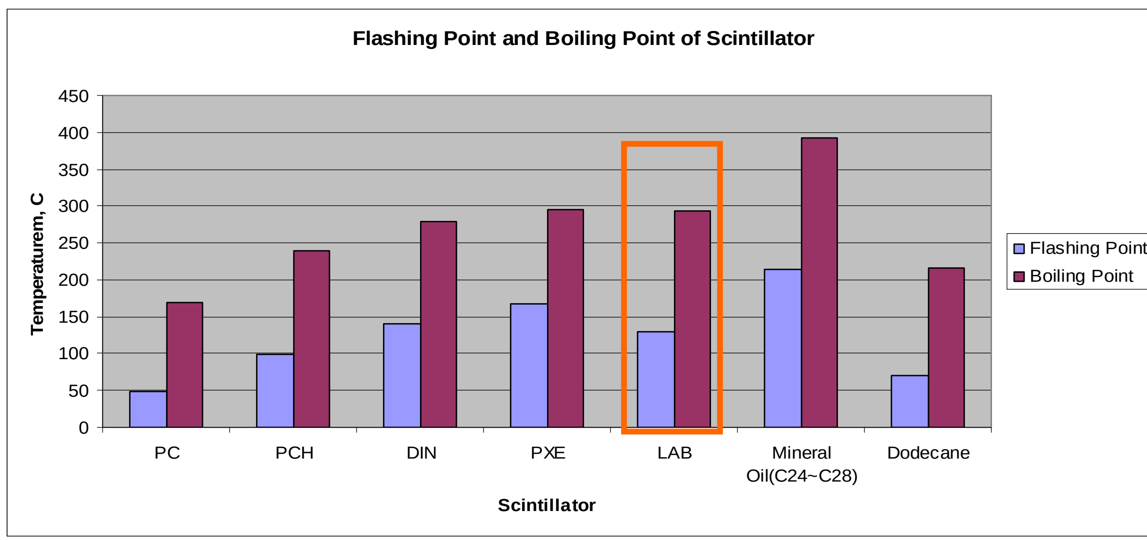
LAB is attractive:

- *High flashpoint*
- *Biodegradable*
- *Millions of tons of it are produced annually for detergent industry*

linear alkyl chains of 10-13 C atoms with a benzene ring; used primarily for the production of biodegradable synthetic detergent

Boiling Point (°C)	*275 - 307*
Melting Point (°C)	*< -50*
Flash Point (°C)	*130*
Vapor Pressure (mmHg)	*< 0.1 mmHg @ 20°C*
Vapor Density (Air =1)	*8.1*
Solubility in Water	*Insoluble*
Molecule Weight	*233 – 237 g/mol*
pH	*Not applicable*
Viscosity	*5 – 10 cps @ 20°C*
Evaporation Rate (water =1)	*Not applicable*

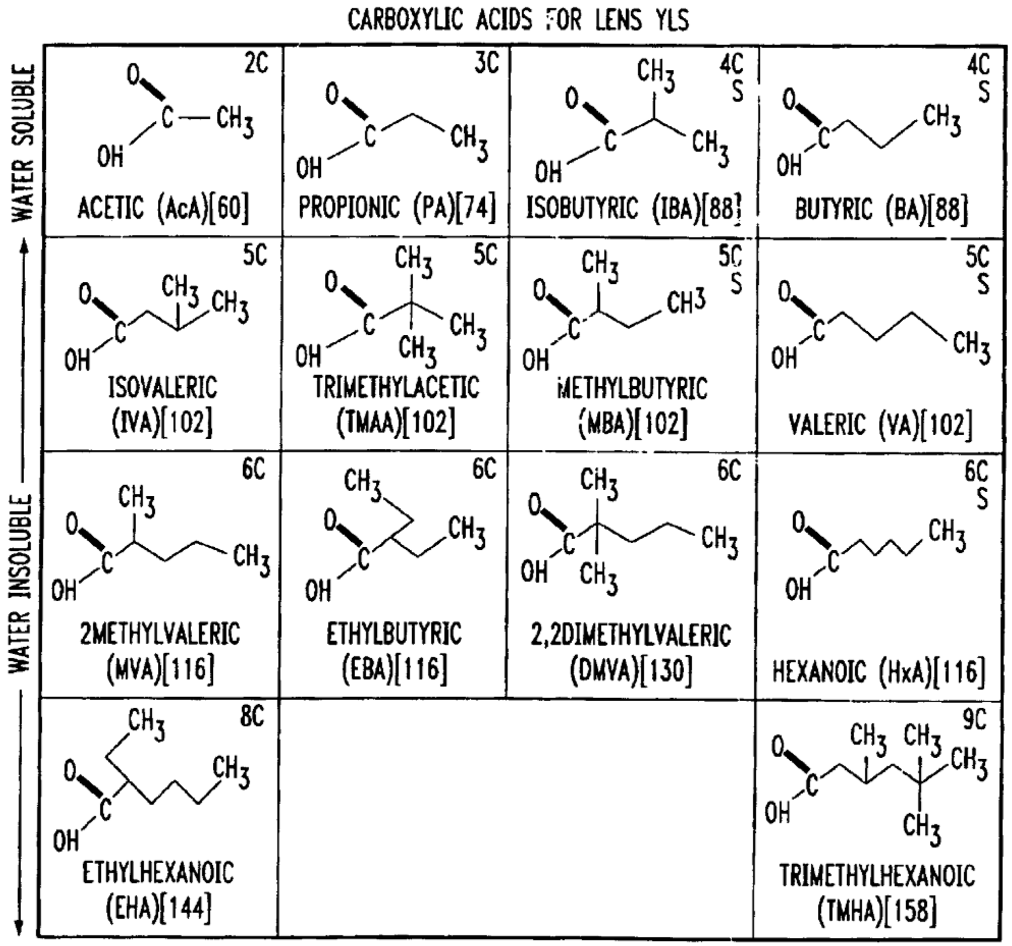




Selection of Extractant

Extractant	Gd form in LS	Comparison
alcohols	**$GdCl_3.6H_2O$**	**$GdCl_3$ quickly dissolved in the mixture of alcohol and PC; low light yield and not stable possibly due to quenching effect and high vapor pressure .**
P=O compounds	**$Gd(carboxylate)_x.(Cl)_y.(OH)_z.(H_2O)_a.(TOPO)_b$**	**high extraction efficiency; moderate attenuation length; not stable for long term (phosphorus might interact with other compounds; CHOOZ experience of NO_3)**
carboxylic acid	**$Gd(carboxylate)_x.(Cl)_y.(OH)_z.(H_2O)_a$**	**high extraction efficiency; long attenuation length; high light yield; very stable (>14 months for Gd-LS and over 2.5 years for In-LS since synthesis)**

Selection of Carboxylic Complexing Ligands



Different carboxylic acids for different metal ions

Loading concentration

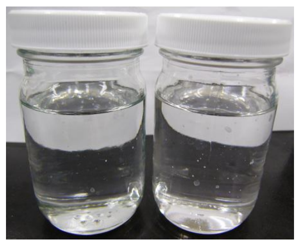
Loading efficiency

Light yield

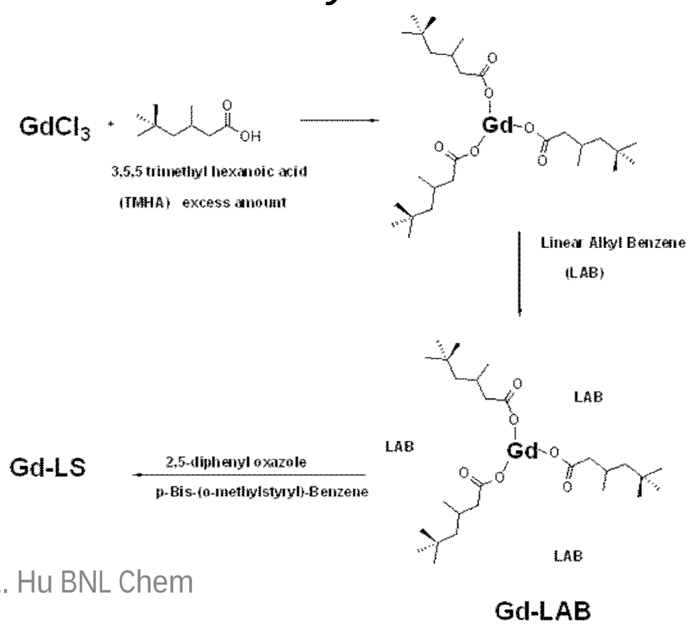
Synthesis of M-LS

Solvent Extraction vs. Solid dissolution

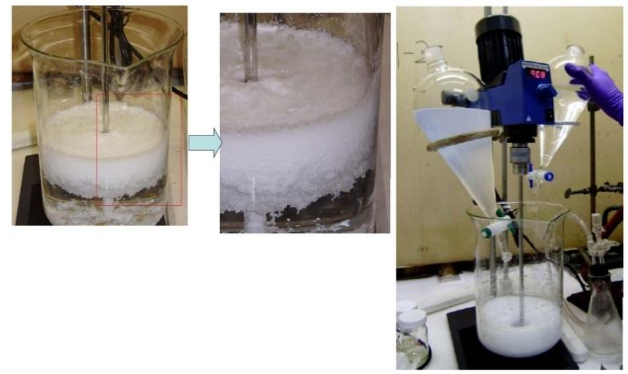
LAB + Carboxylic acid (in H_2O)+MCl_3 (in H_2O)



Remove water layer



Carboxylic Acid (in H_2O)+MCl_3 (in H_2O)

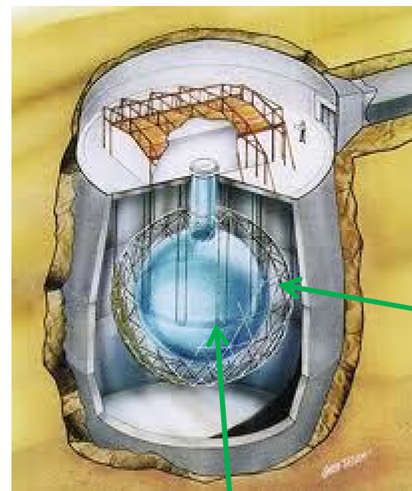


Collect the solid
Wash
Dissolve the solid in LAB
Wait for it to get cleared
Leach out the additional water

Nd-loaded LS for SNO+

1-k tons of 0.1% Nd in Liquid Scintillator

- *Neutrinoless double beta decay (^{150}Nd)*
- *Determine the mass/nature of the neutrino*



“rope basket”

Acrylic vessel

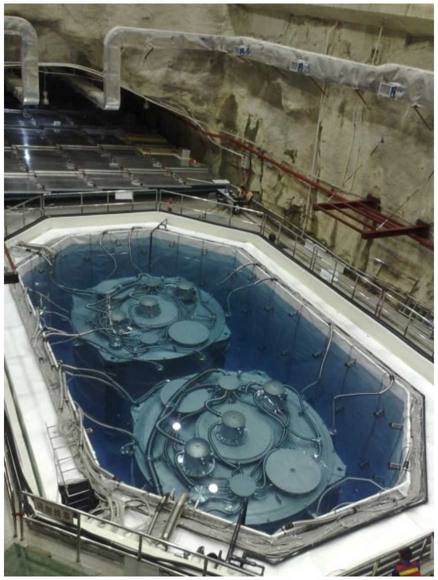
SNO’s ultra-pure water systems will be replaced by similar purification systems that can eliminate trace radioactivity from an organic liquid scintillator

<u>*Gd-loaded LS for Daya Bay*</u>

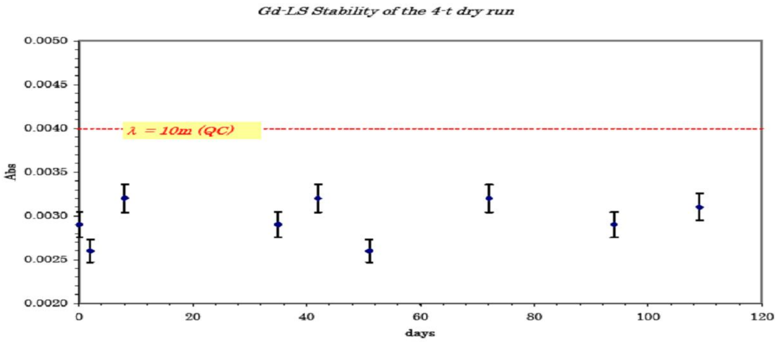
200 ton 0.1% gadolinium-loaded liquid scintillator (Gd-LS)

Measure reactor $\bar{\nu}$ for θ_{13} at 1%

Gd-LS was produced in multiple batches but mixed in reservoir on-site, to ensure identical detectors.



Detectors in Hall 1

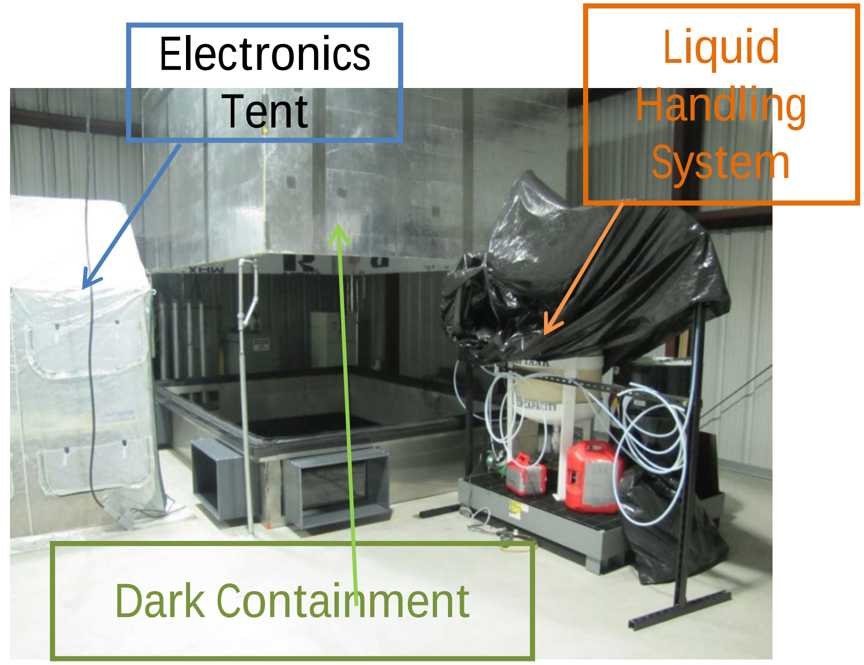


In-loaded LS for LENS

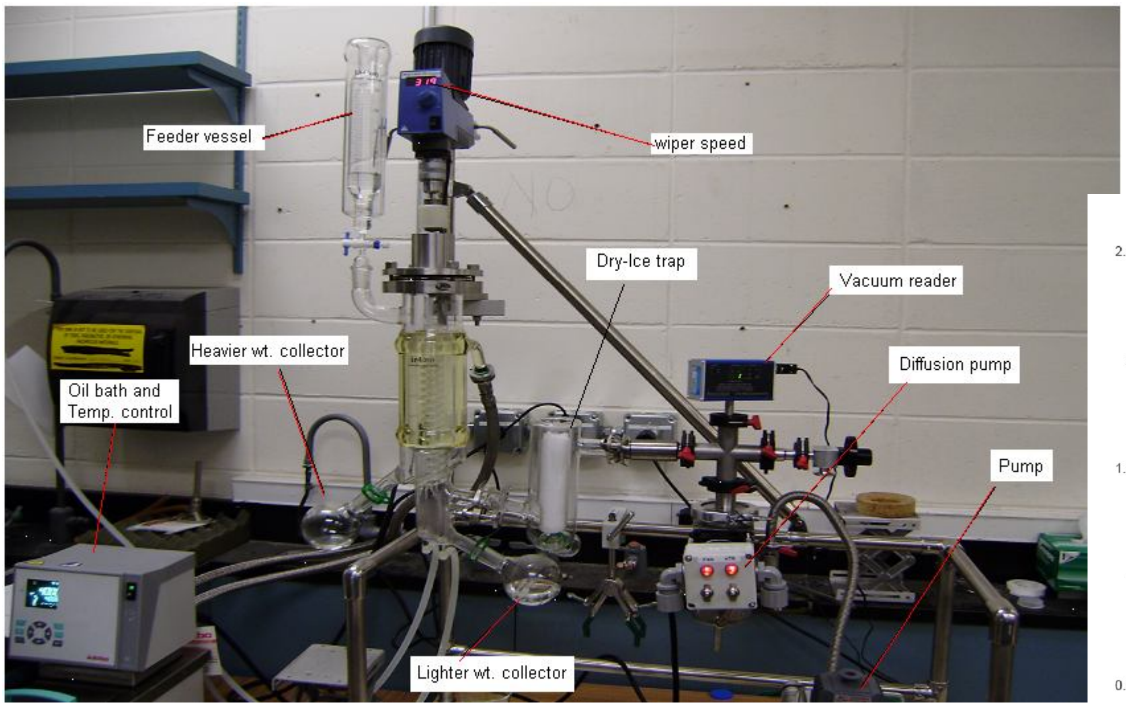
125 tons of ~8% ^{115}In Liquid Scintillator for full scale LENS

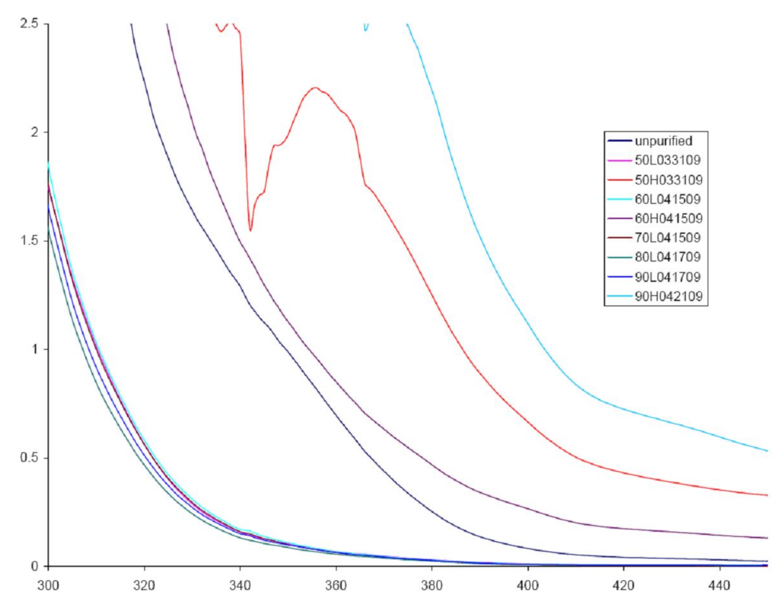
- *The real time primary low energy (sub-MeV) solar neutrino spectrum*
- *Solar metallicity and luminosity*

A view inside KURF from above microLENS liquid handling



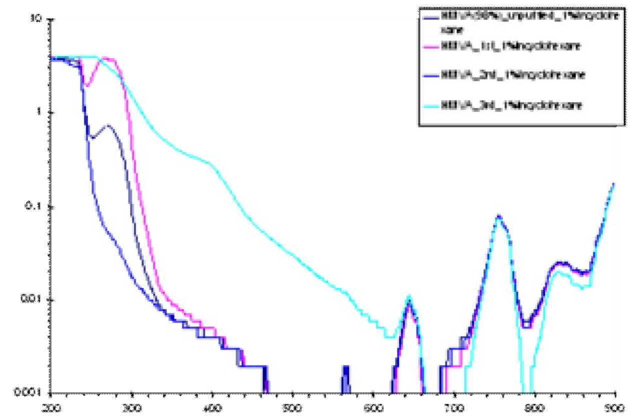
Purification of Water and TMHA

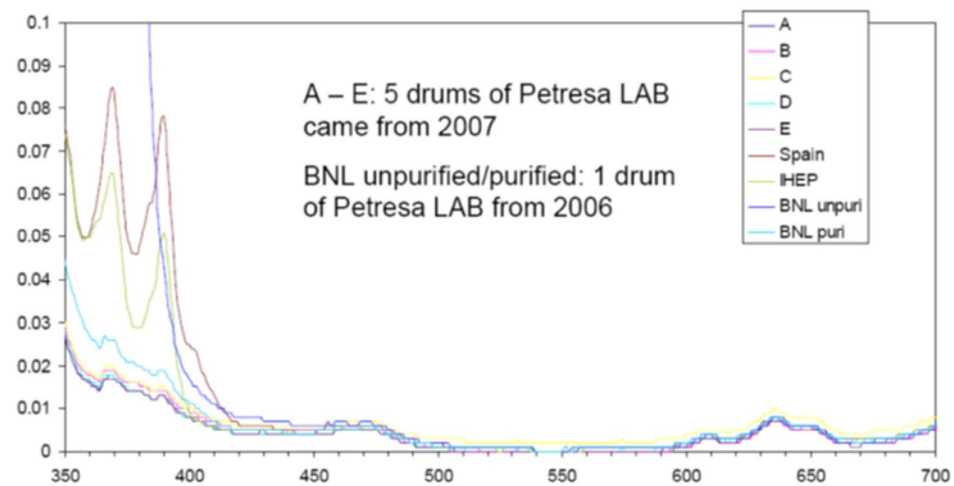




Purification of HMVA and LAB

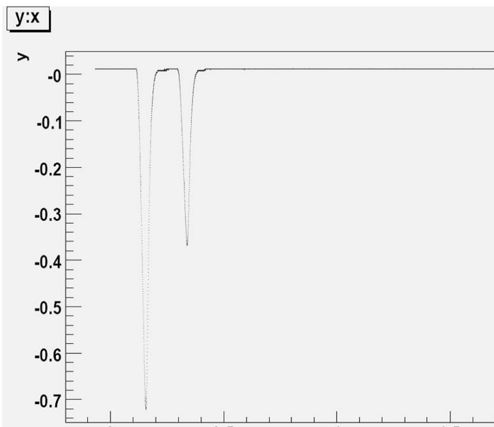
- Automatic distillation of HMVA
- Dry column purify LAB



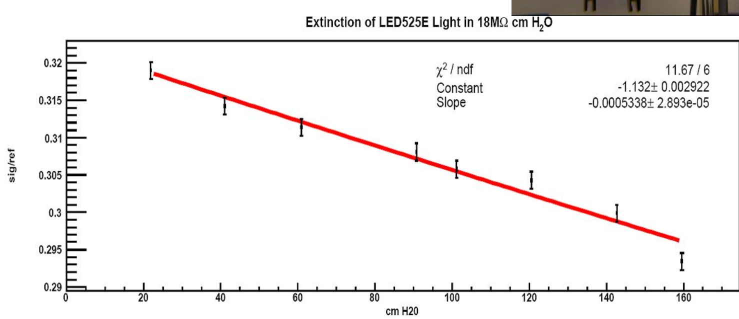


M-LS Characterization (I)

- $L_{1/e}$ (att. length) by 2-m dual-beam, vertical LED system.

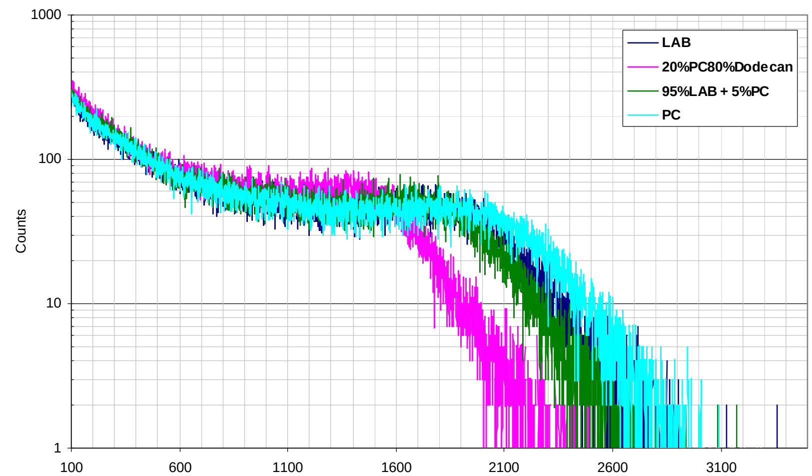


$$\mathcal{L} = \frac{\log(e)L}{A(L)}$$

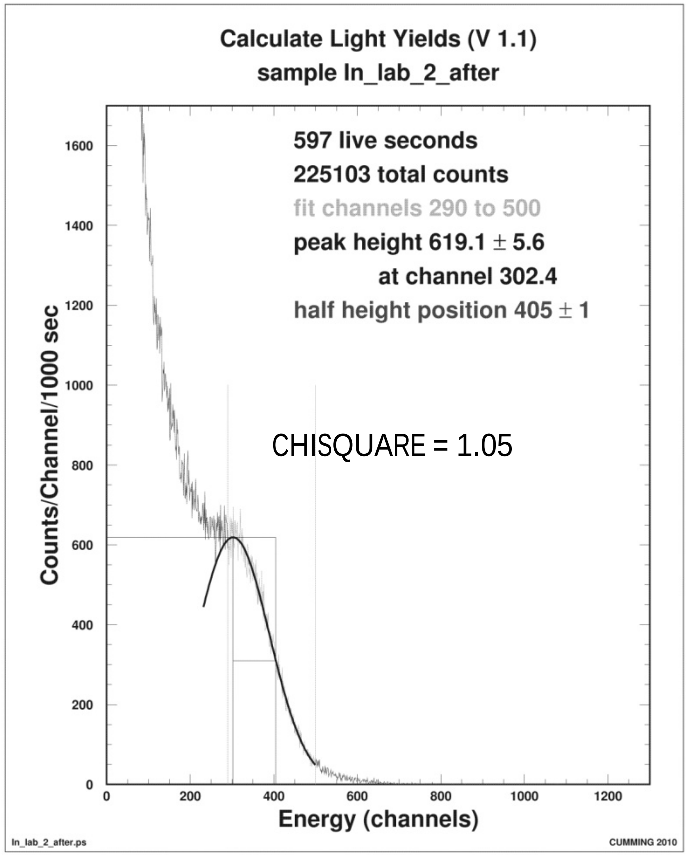


18.9±1.2m for 18MΩ H_2O at 525nm, J. Goett

- Light Yield (S%)

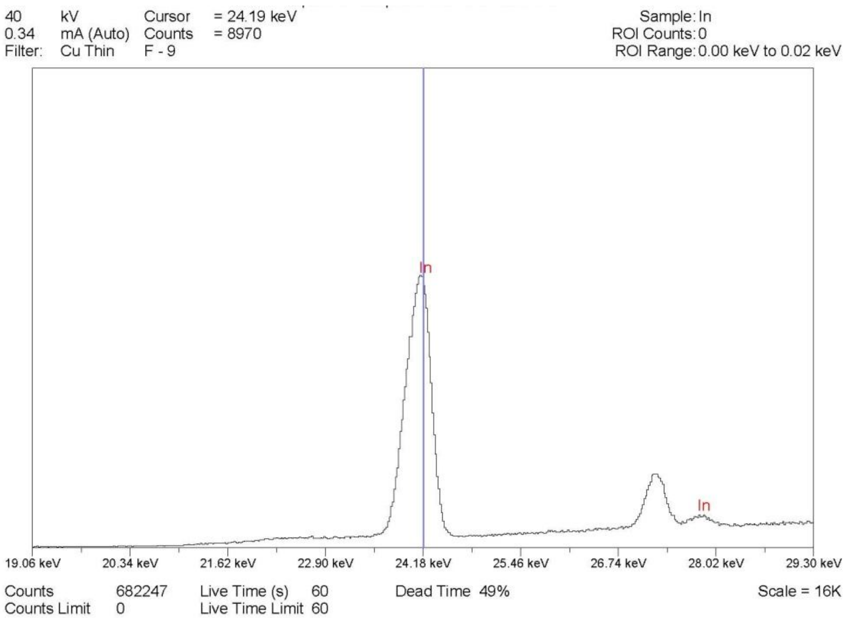


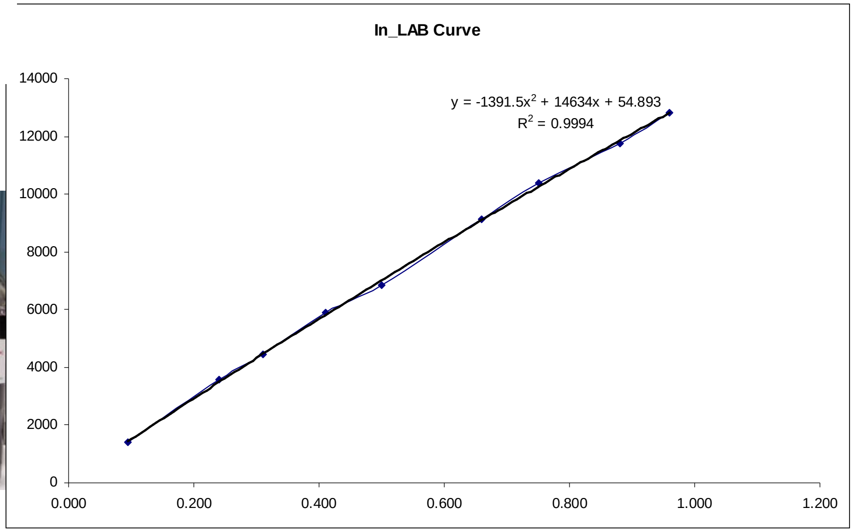
Light Yield Percentage Calculated Program



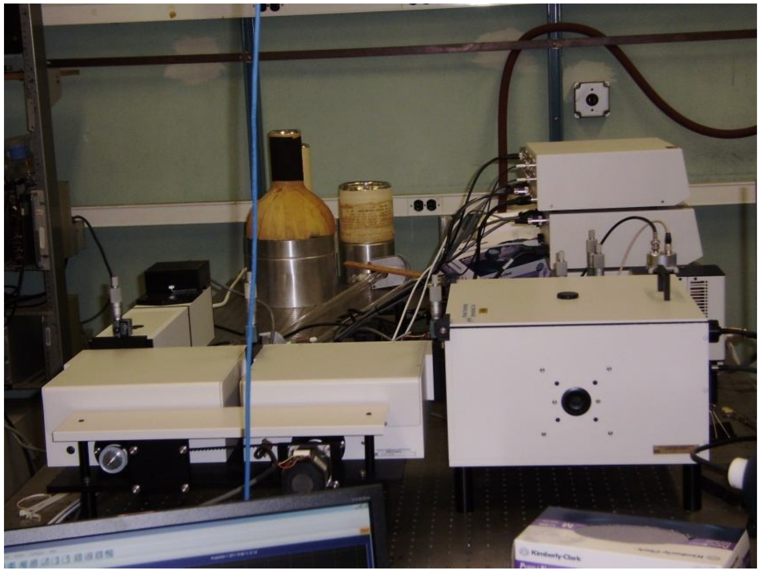
M-LS Characterization (II)

- [M^{n+}] by XRF and UV





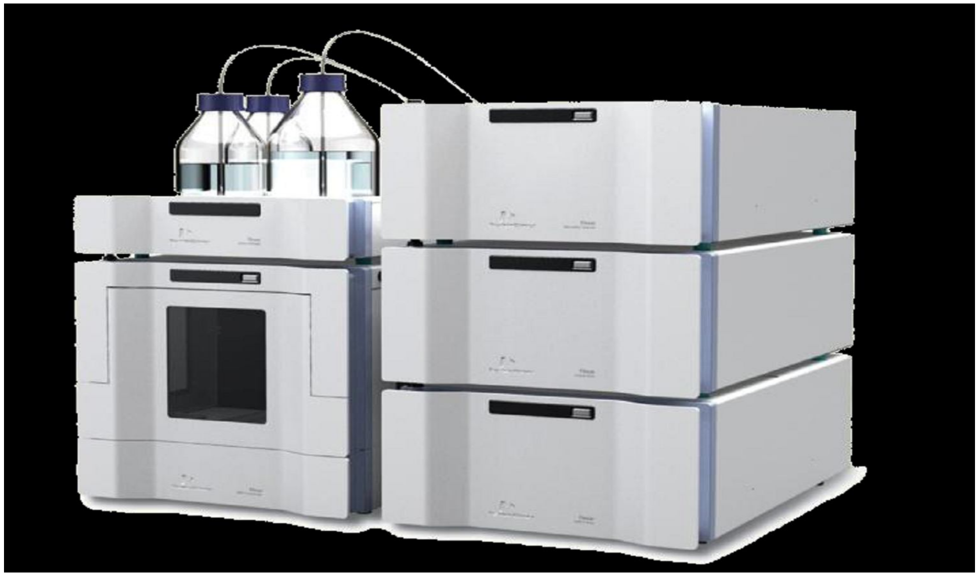
M-LS Characterization (III)



IR
Qualification and quantification

Florescence Spectrometer
Excitation, Emission, and lifetime of LS

M-LS Characterization (IV)



GC/MS
Impurities of chemicals

LC/MS
Materials compatibilities

Summary

- *M-loaded LS becomes one of main-stream detection mediums from the past 5 years.*
- *BNL is one of the facility that has the expertise and equipments for all-aspect development of organometallic liquid scintillator including (1) synthesis, (2) characterization and (3) purification of M-LS.*
- *A variety of metallic ions has been loaded into liquid scintillator at different concentrations (0.1 – 10%) with high-quality, large-scale production (> hundreds of tons) of M-LS for different neutrino experiments*
  - *M-LS are stable for long period of time (>3.5 yrs for 10% In-LS; >2 yrs for 1% Nd-LS; and >3 yrs for 0.1% Gd-LS).*
- *M-LS use of veto or calibration are under development.*

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